SPARC: A Security and Privacy Aware Virtual Machine Checkpointing Mechanism

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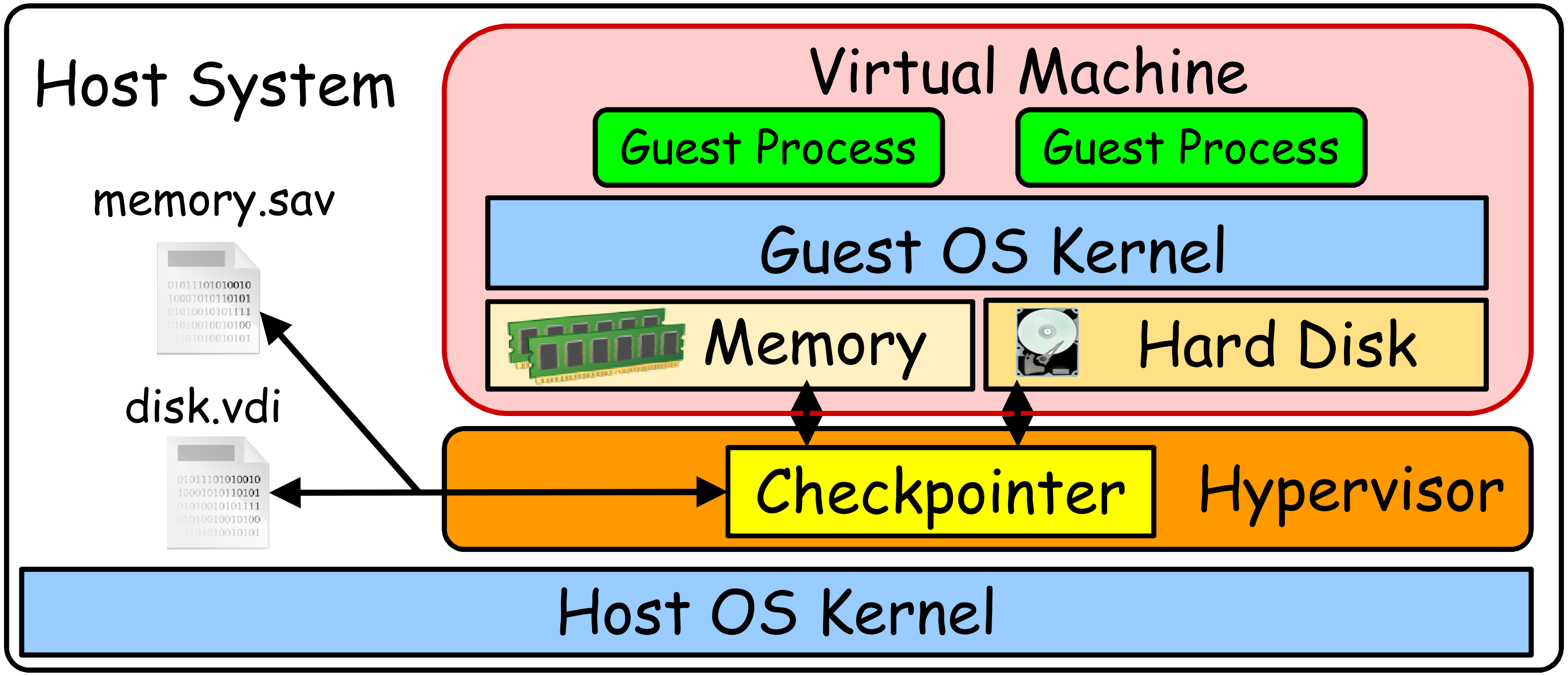
Outline

- Background: Virtual Machine (VM) Checkpointing
- SPARC: a Security and Privacy Aware Checkpointing Mechanism
- Experiments and Performance Results

Virtual Machine (VM) Checkpointing

- Virtual machine checkpointing saves a snapshot of the physical memory and disk state of a VM in execution:
  - Example: Checkpointing in VirtualBox:
    - Checkpointing: saves the VM physical memory to a .sav file and disk state to a .vdi file.
    - Restoration: rolls back the disk state and loads the .sav file into VM memory.

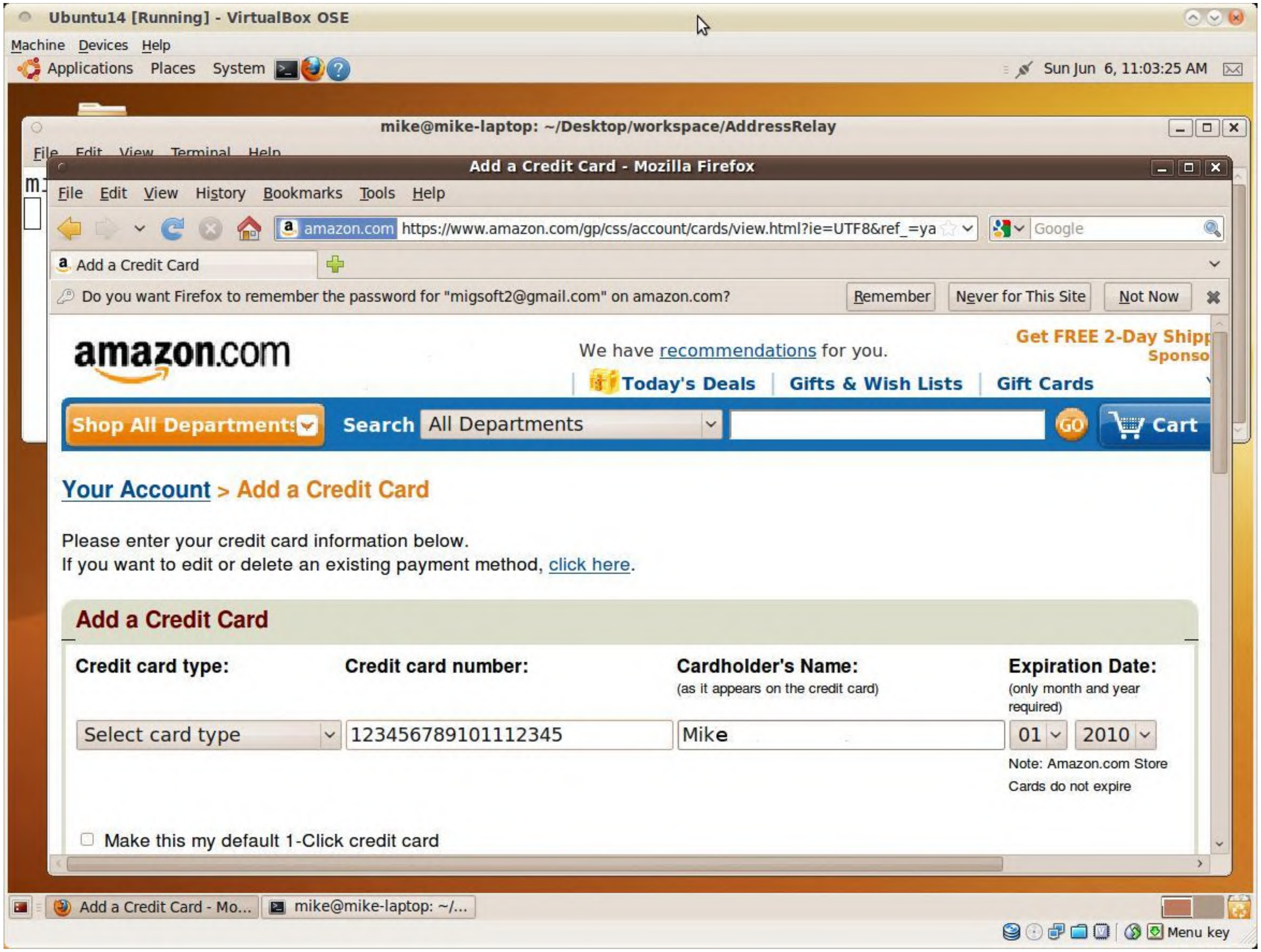


Virtual Machine (VM) Checkpointing: Benefits and Risks

- Benefits:
  - Easy recovery of a long running process after it crashes.
  - Easily undo damages caused by malware, patches, etc.
- Security Risks:
  - VM memory may contain passwords, credit card #'s, and other sensitive information that should be quickly discarded after usage.
  - Checkpointing drastically prolongs the lifetime of such data by saving it to persistent storage.

Security Issue: Virtual Machine Checkpointing

- VM checkpoint created/restored using VirtualBox's default checkpointing mechanism:



Ubuntu14 [Running] - VirtualBox OSE

mike@mike-laptop: ~/Desktop/workspace/AddressRelay

Add a Credit Card - Mozilla Firefox

https://www.amazon.com/gp/css/account/cards/view.html?ie=UTF8&ref_=ya

Do you want Firefox to remember the password for "migsoft2@gmail.com" on amazon.com?

We have recommendations for you.

Your Account > Add a Credit Card

Please enter your credit card information below.
If you want to edit or delete an existing payment method, click here.

Add a Credit Card

Credit card type:	Credit card number:	Cardholder's Name: (as it appears on the credit card)	Expiration Date: (only month and year required)
Select card type	123456789101112345	Mike	01 2010 Note: Amazon.com Store Cards do not expire

□ Make this my default 1-Click credit card

Problem Statement

- Problem: How can we prevent sensitive data from being leaked via VM checkpoints?
- Solution: Prevent sensitive data from being stored in the checkpoint file.

Existing Approaches

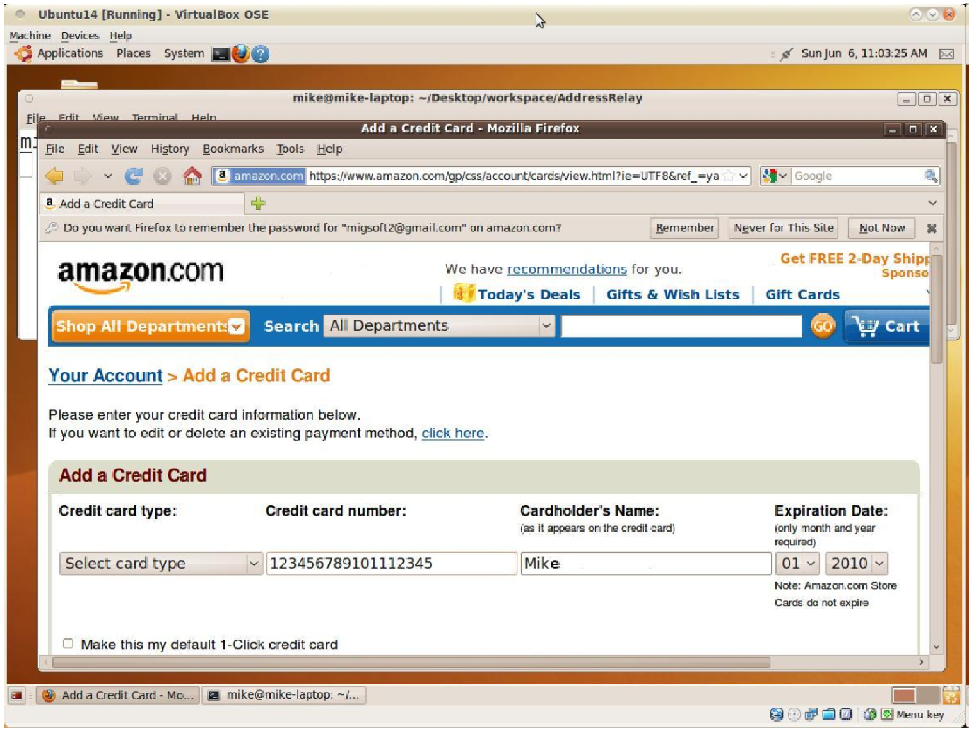
- Clearing deallocated memory:
  - Does not prevent memory pages from being checkpointed before they are deallocated.
- Protect the checkpointed information by encrypting the checkpoint files:
  - Restoration decrypts the checkpoint file and loads it into the memory of the VM, thus making the sensitive information vulnerable again.
  - Attacker can compromise the user's account and gain access to sensitive data by restoring the checkpoints.

Contribution

- We developed SPARC: a Security and Privacy Aware Checkpointing mechanism:
  - Enables the users to exclude applications containing user's sensitive information from being checkpointed.

SPARC in Action

- Left: VM checkpoint created/restored using VirtualBox default mechanism.
- Right: VM checkpoint created/restored using SPARC with Firefox excluded from the checkpoint.


Ubuntu14 [Running] - VirtualBox OSE
Machine Devices Help
Applications Places System
Sun Jun 6, 11:03:25 AM
mike@mike-laptop: ~/Desktop/workspace/AddressRelay
Add a Credit Card - Mozilla Firefox
File Edit View History Bookmarks Tools Help
amazon.com https://www.amazon.com/gp/css/account/cards/view.html?ie=UTF8&ref_=ya
Google
Add a Credit Card
Remember
Never for This Site
Not Now
amazon.com
Get FREE 2-Day Shipp
Sponso
Today's Deals
Gifts & Wish Lists
Gift Cards
Shop All Departments
Search
All Departments
GO
Cart
Add a Credit Card - Mo...
mike@mike-laptop: ~/...
Menu key

Do you want Firefox to remember the password for "migsoft2@gmail.com" on amazon.com?

We have recommendations for you.

Your Account > Add a Credit Card

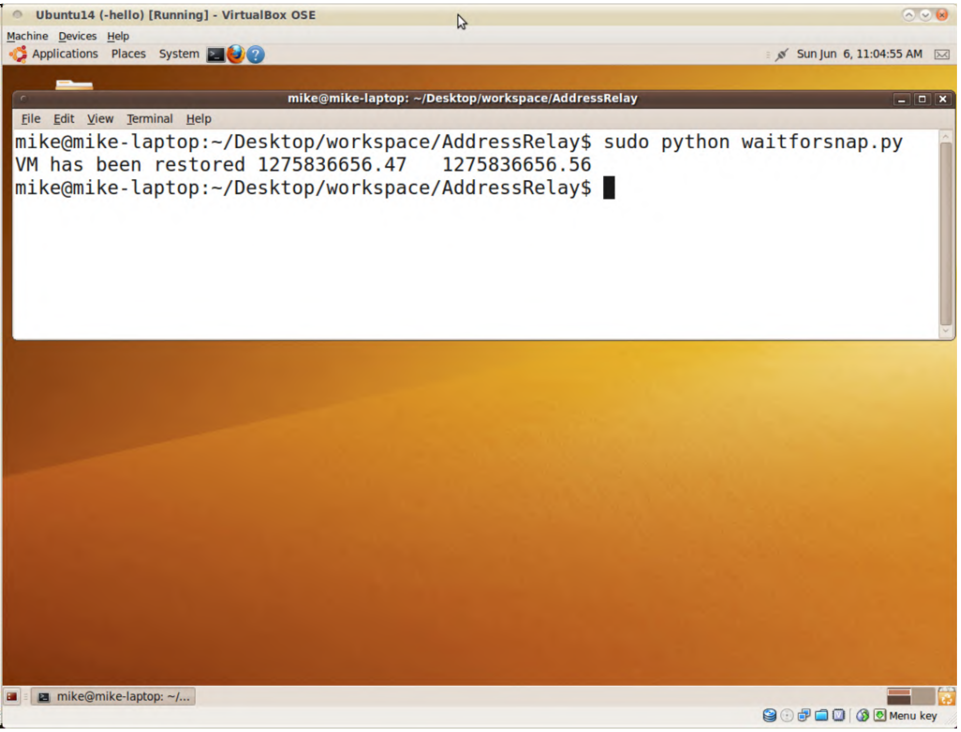
Please enter your credit card information below.
If you want to edit or delete an existing payment method, click here.

Add a Credit Card

Credit card type:	Credit card number:	Cardholder's Name: (as it appears on the credit card)	Expiration Date: (only month and year required)
Select card type	123456789101112345	Mike	01 2010

Note: Amazon.com Store Cards do not expire

□ Make this my default 1-Click credit card

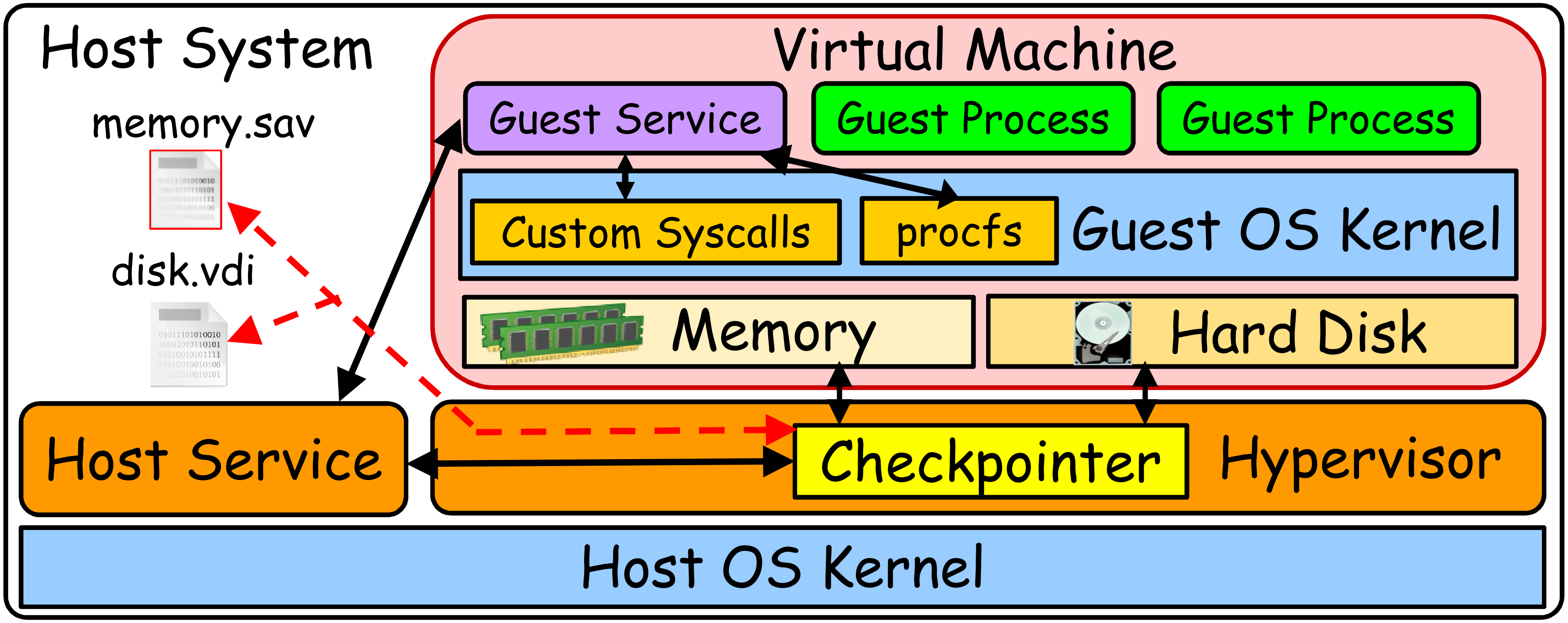

Ubuntu14 (-hello) [Running] - VirtualBox OSE
Machine Devices Help
Applications Places System
Sun Jun 6, 11:04:55 AM
mike@mike-laptop: ~/Desktop/workspace/AddressRelay
File Edit View Terminal Help
mike@mike-laptop: ~/...
Menu key

```
mike@mike-laptop:~/Desktop/workspace/AddressRelay$ sudo python waitforsnap.py
VM has been restored 1275836656.47   1275836656.56
mike@mike-laptop:~/Desktop/workspace/AddressRelay$ █
```

SPARC: Key Idea

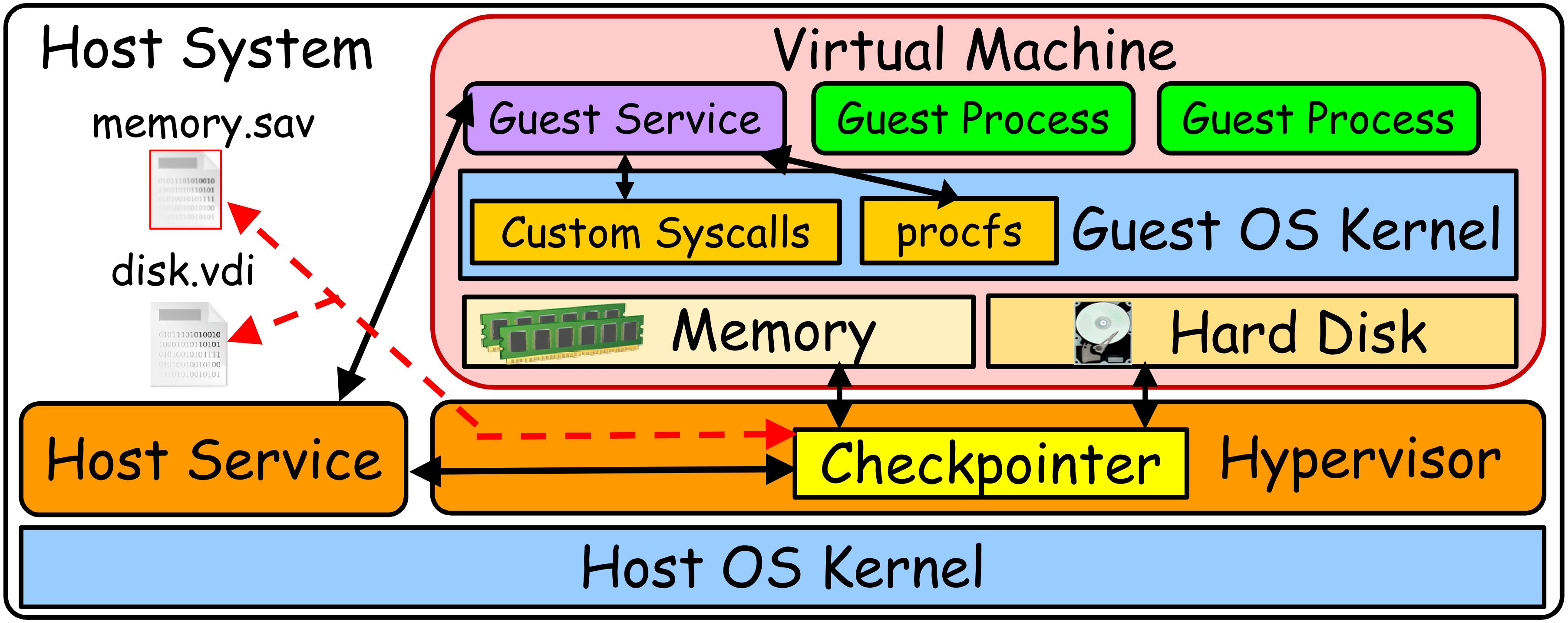
- Track all memory pages containing information related to all privacy sensitive applications and exclude such memory from the checkpoint.

SPARC Architecture



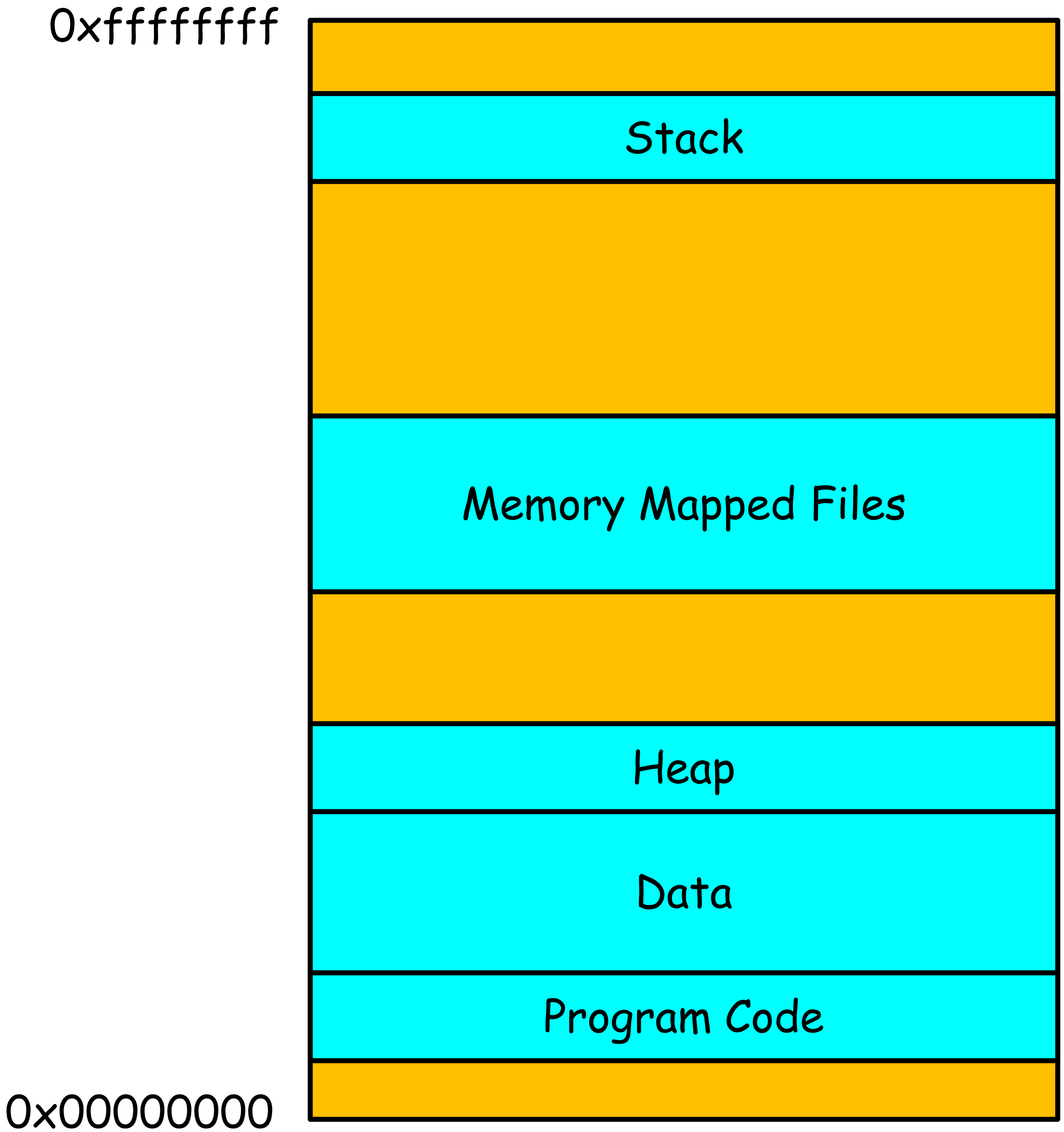
- Guest Service: executes inside the VM, detects physical memory addresses of a process to be excluded, and sends them to the host service.
  - procfs (process file system): used to identify physical pages belonging to the process.
  - Custom System Calls: used to identify kernel physical memory of a process.

SPARC Architecture (Contd).



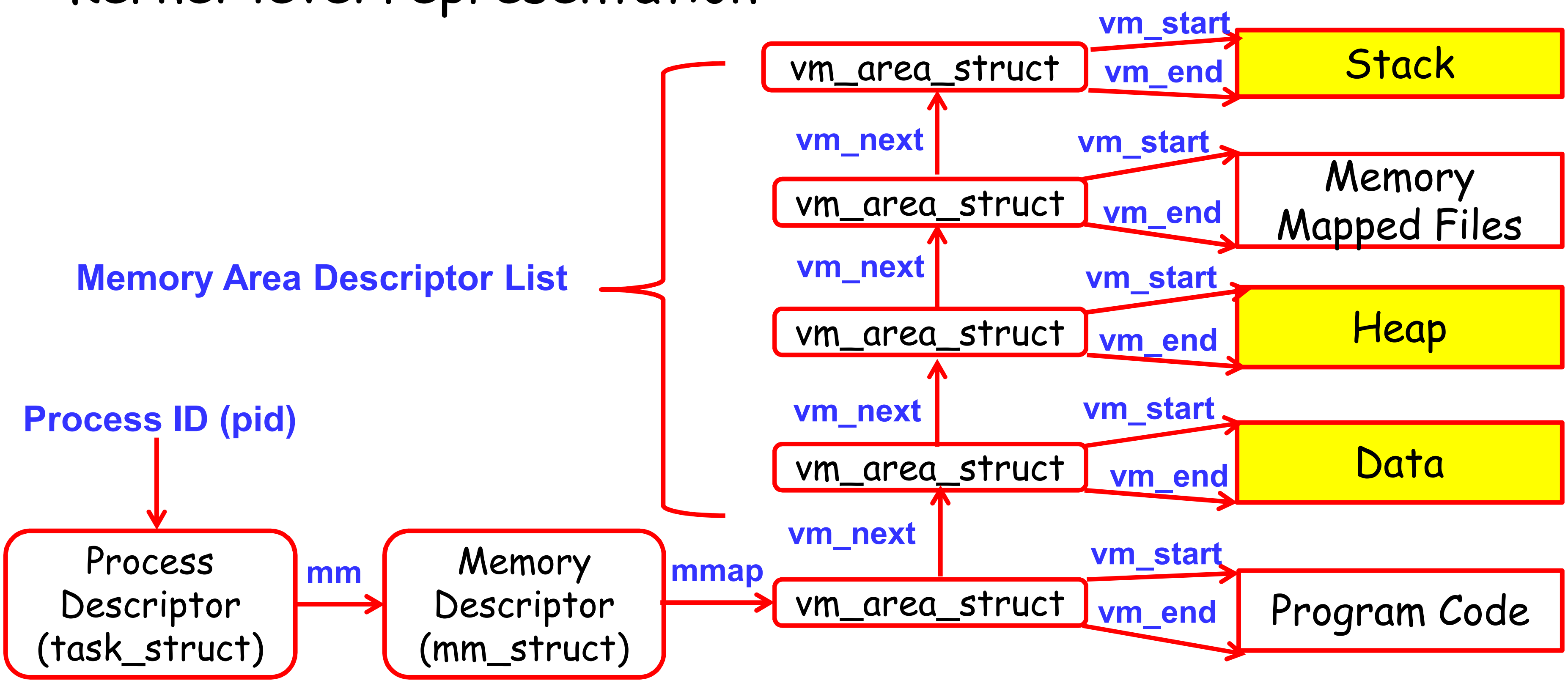
- Host Service: receives the physical addresses from the guest service and tells the VirtualBox checkpointer to avoid checkpointing these addresses.

Process Virtual Address Space



Identifying Virtual Memory of the Process

- Kernel-level representation:



- We traverse the list of memory area descriptors (vm_area_structs) and collect starting/ending virtual addresses of only stack, heap, and data regions.

Converting Virtual Addresses to Physical

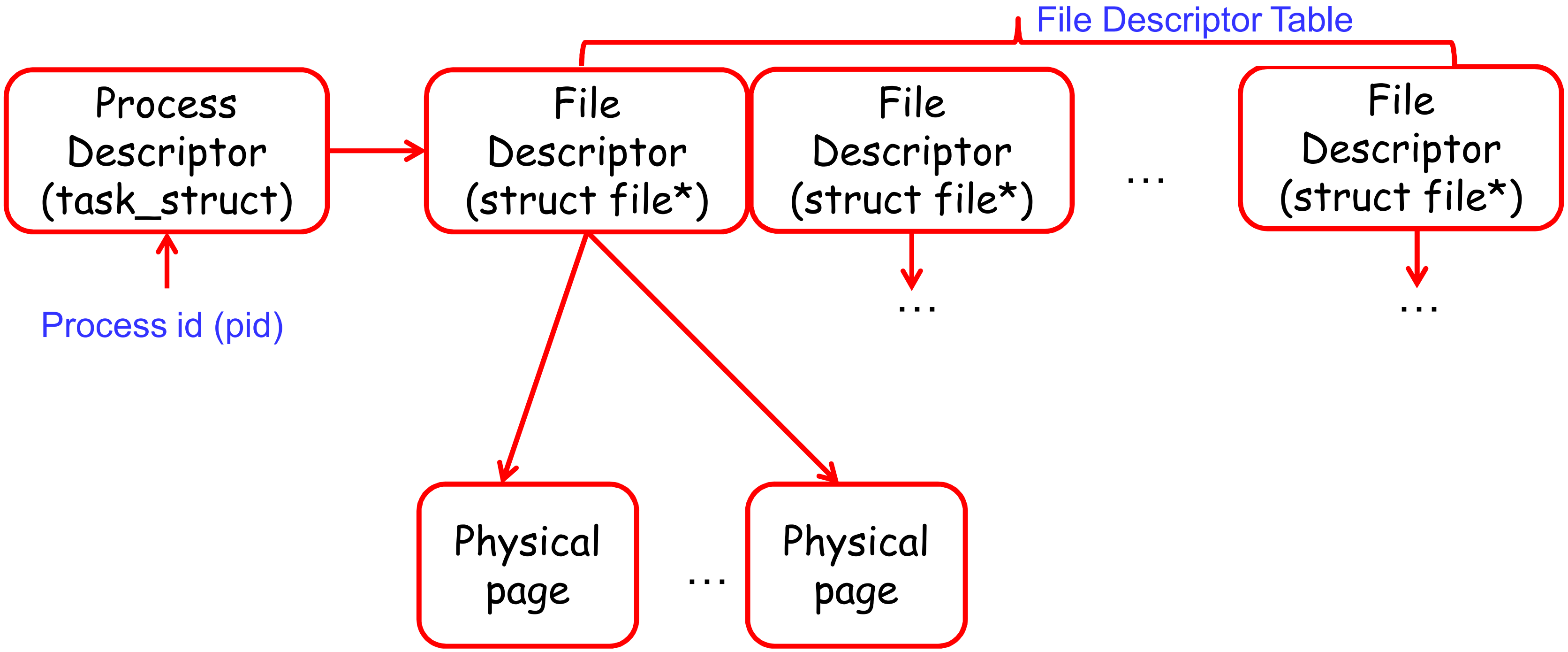
- Break up virtual memory sections into physical pages and look up corresponding physical addresses in /proc/pid/pagemap file.

- Problem: virtual-to-physical mappings may change after the physical addresses are collected.

- Solution:
  - Freeze all processes in the VM except the guest service prior to address collection.
  - Thaw after checkpointing completes and after restoration.
  - Modify kernel to scrub deallocated memory of the process.

Excluding pages in the page cache

- May contain sensitive information that the process has read/written to/from the file.
  - Such pages must be excluded from the checkpoint file.


File Descriptor Table
Process Descriptor (task_struct)
Process id (pid)
File Descriptor (struct file*)
File Descriptor (struct file*)
…
File Descriptor (struct file*)
…
…
Physical page
…
Physical page

Excluding pages in the page cache (Contd.)

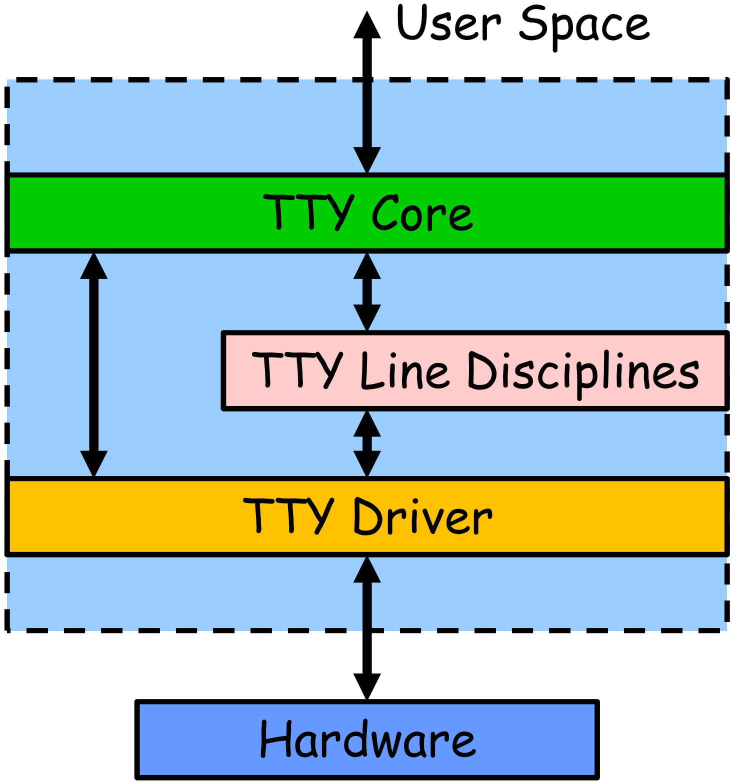
- Problem: After restoration, excluded pages in page cache may affect other processes sharing the same pages.
- Solution: Evict all excluded pages after the VM is restored.
- Problem: Page cache may retain contents even after a file is closed by a process.
- Solution:
  - Evict all pages belonging to such files when the process closes the file.
  - Always clear evicted pages belonging to such files.

Pipe, FIFO, and Socket Buffers

- Process to be excluded may communicate with other processes through pipes, FIFOs, and sockets.
- Excluding pipe and socket buffers:
  - Detect file descriptors representing pipes/FIFOs/sockets (similar to detecting descriptors for disk files).
  - Get the physical addresses from the pipe buffer (pipe_buffer) and socket buffer descriptors (sk_buff) associated with the file descriptor.

Excluding Terminal Applications

- Why exclude terminal applications?
  - Processes may input/output sensitive information to/from the terminals they run on.
- Two types of terminals: Virtual Consoles and Pseudo Terminals
- Terminal applications rely on the Teletype subsystem (TTY) in the kernel.
- Each level of TTY contains buffers which may store sensitive data from the process.



Excluding Terminal Applications

- Excluding Virtual Consoles:
  - Must detect and exclude all processes running on the console to be excluded:
    - Each process descriptor (task_struct) contains a pointer to the tty_struct representing the associated console.
    - Exclude the process and all its descendants.
- Excluding pseudo terminals: similar to excluding Virtual Consoles:
  - Difference: must also exclude the associated pseudo terminal driver (pty).

Handling Restoration

- After restoration we kill the excluded process to allow the OS to clean up any residual state.
- SPARC does not affect the present execution of the VM since the memory is only cleared from the checkpoint file (i.e. not the VM RAM).

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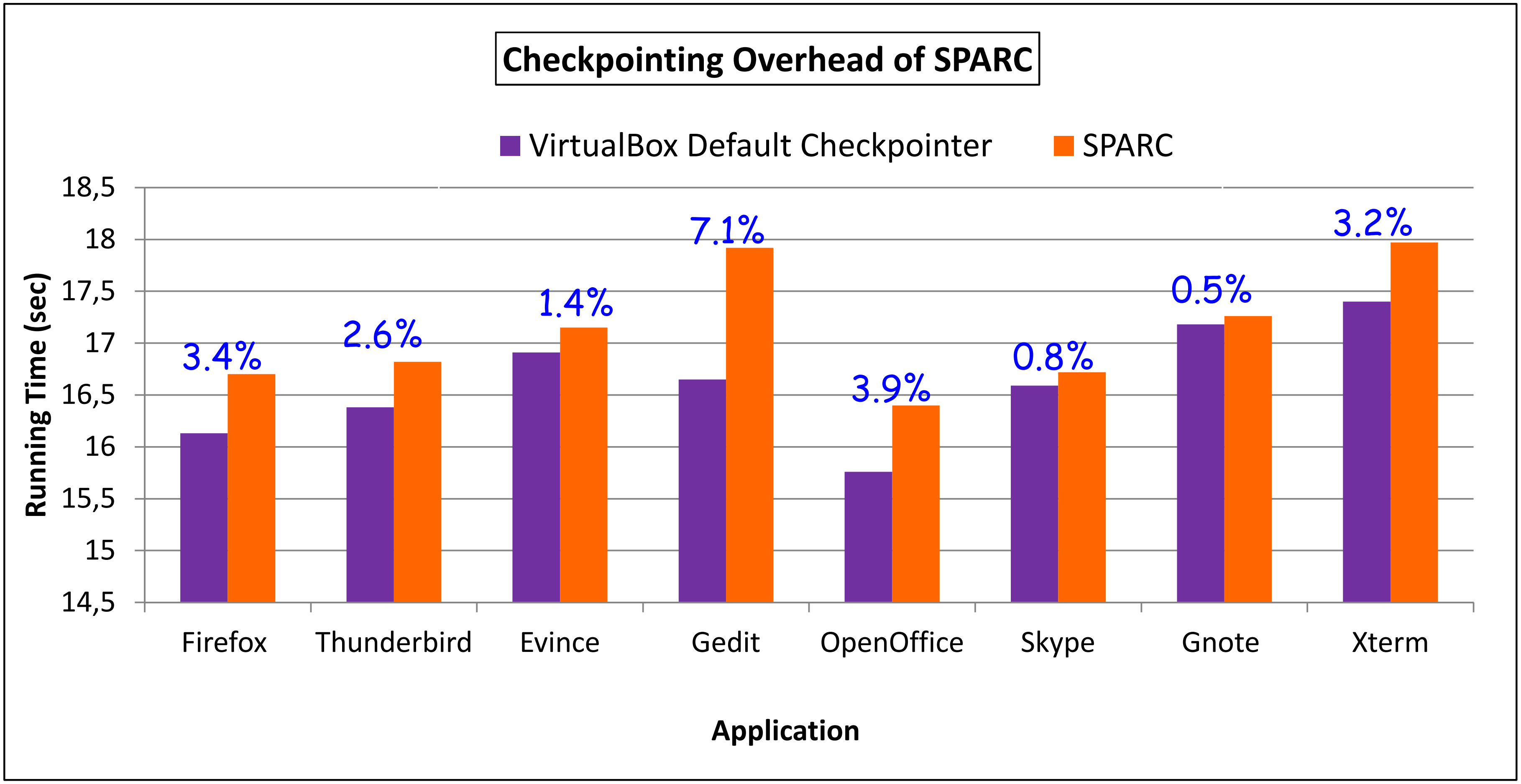
Evaluating SPARC's Effectiveness

- Enter a string in xterm terminal, checkpoint the VM, and study the .sav file with a hex editor:
- Without SPARC: string appears 6 times.
- With SPARC:
  - Excluding the memory of xterm and bash: string appears 3 times.
  - Excluding the memory of xterm, bash, and the associated TTY subsystem: string disappears.

Performance Results: Experimental Setup

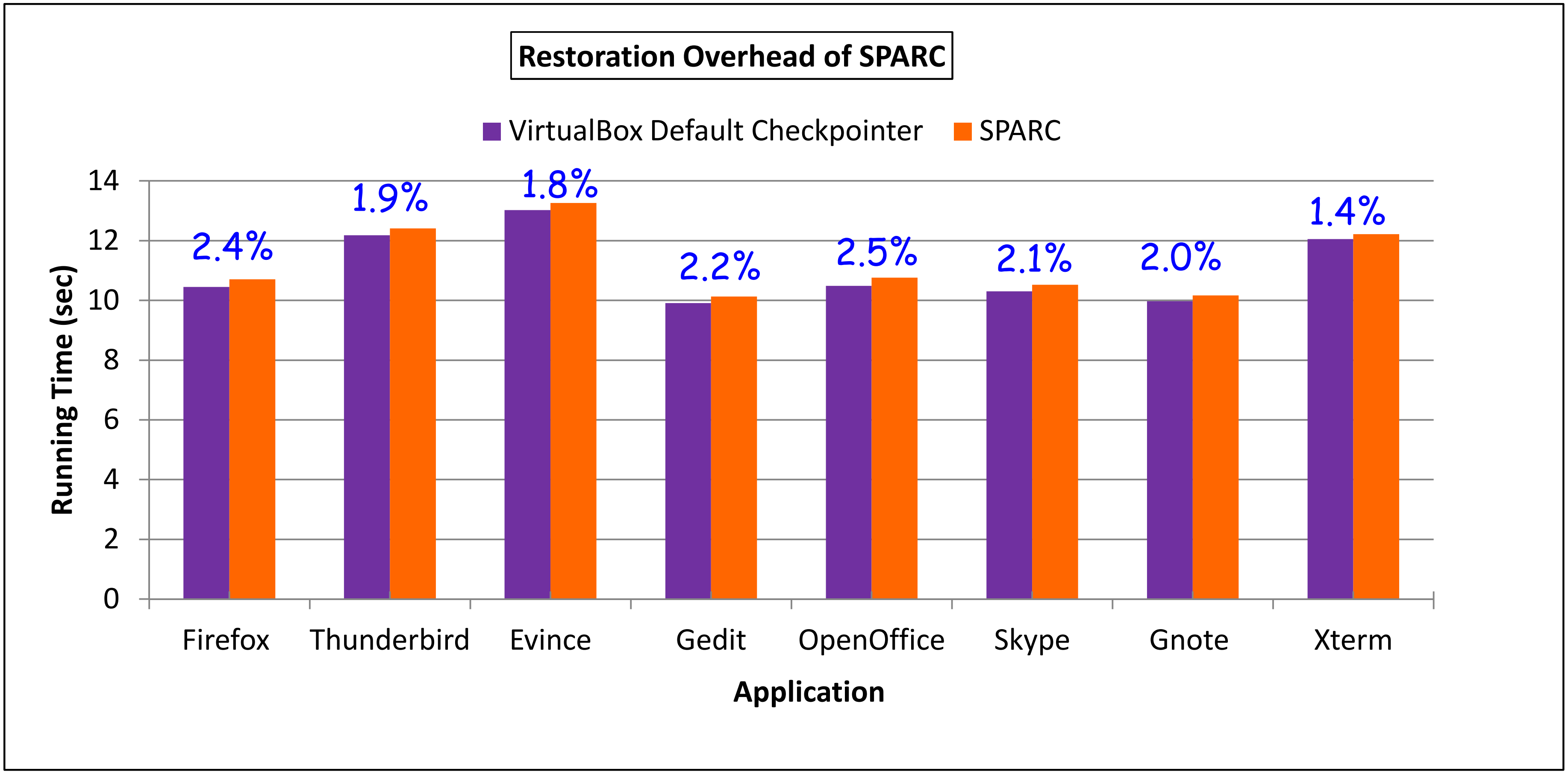
- We compared the execution times for creating/restoring checkpoints using VirtualBox default checkpointing mechanism and SPARC.
- Experimental Setup:
  - Freshly booted VM running system services, guest service, and a process to be excluded.
  - Run a program to dirty most of VM's physical pages:
    - VirtualBox reduces checkpoint file size by checkpointing only dirty pages.
  - Create and restore checkpoint using default mechanism or SPARC and time the operations.
  - Delete the checkpoint and reboot the VM between subsequent runs.
- Each data point is an average of five runs.

Performance Results: Checkpointing Overhead of SPARC



- SPARC imposes 0.5%–7.1% overhead on checkpointing.

Performance Results: Restoration Overhead of SPARC



- SPARC imposes 1% – 5.3% overhead on restoration.

Conclusions and Future Work

- Conclusions:
  - VM checkpointing can drastically prolong the lifetime of sensitive data by saving it to the checkpoint.
  - SPARC reduces the lifetime of sensitive data by preventing unintended checkpointing of process-specific memory contents.
- Future Work:
  - Detecting and excluding all non-system critical processes that communicate with the process to be excluded.
  - Extend SPARC to exclude confidential disk information from being checkpointed.
  - Excluding sensitive data displayed on the GUI.

Thank You!

Questions?